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Is the Effect of a Countermovement on Jump Height due to Active State Development?

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ABSTRACT

BOBBERT, M. F., and L. J. R. CASIUS. Is the Effect of a Countermovement on Jump Height due to Active State Development? *Med. Sci. Sports Exerc.*, Vol. 37, No. 3, pp. 440–446, 2005. **Purpose:** To investigate whether the difference in jump height between countermovement jumps (CMJ) and squat jumps (SJ) could be explained by a difference in active state during propulsion. **Methods:** Simulations were performed with a model of the human musculoskeletal system comprising four body segments and six muscles. The model's only input was STIM, the stimulation of muscles, which could be switched "off" or "on." After switching "on," STIM increased to its maximum at a fixed rate of change (dSTIM/dt). For various values of dSTIM/dt, stimulation switch times were optimized to produce a maximum height CMJ. From this CMJ, the configuration at the lowest height of the center of gravity (CG) was selected and used as static starting configuration for simulation of SJ. Next, STIM-switch times were optimized to find the maximum height SJ. **Results:** Simulated CMJ and SJ closely resembled jumps of human subjects. Maximum jump height of the model was greater in CMJ than in SJ, with the difference ranging from 0.4 cm at infinitely high dSTIM/dt to about 2.5 cm at the lowest dSTIM/dt investigated. The greater jump height in CMJ was due to a greater work output of the hip extensor muscles. These muscles could produce more force and work over the first 30% of their shortening range in CMJ, due to the fact that they had a higher active state in CMJ than in SJ. **Conclusion:** The greater jump height in CMJ than in SJ could be explained by the fact that in CMJ active state developed during the preparatory countermovement, whereas in SJ it inevitably developed during the propulsion phase, so that the muscles could produce more force and work during shortening in CMJ. **Key Words:** COUNTERMOVEMENT JUMP, SQUAT JUMP, STRETCH-SHORTENING CYCLE, SIMULATION MODEL, FORCE DEVELOPMENT, ELASTIC ENERGY

There is ample evidence that making a countermovement enhances performance in fast discrete movements (1,2,10,16,20). For example, subjects achieve a greater jump height in a so-called countermovement jump (CMJ) in which they start from an upright standing position and make a downward movement before starting to move upward, than in a so-called squat jump (SJ) in which they start from a semisquatted position and make no preparatory countermovement (2,20,21). This is true even if the body configuration at the start of the propulsion phase is the same (1,5) (in the present paper, the term propulsion phase will refer to the phase that starts with upward motion of the center of gravity and ends at take-off). The difference in maximum jump height is on the order of 2–4 cm.

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In the literature, several mechanisms have been proposed to explain the enhancement of maximum jump height by a countermovement. These can best be discussed with the help of Figure 1, which shows for a maximum height CMJ and SJ of one subject the vertical ground reaction force F_z as a function of the height of the center of gravity (CG). The surface under such a plot reflects the change in effective energy, that is, energy contributing to jump height (the sum of potential energy and kinetic energy due to the vertical velocity of CG). If we integrate for the propulsion phase, it is clear that the surface is greater for CMJ than for SJ (the surplus is indicated with the shaded area in Fig. 1), because over most of the range of upward motion of CG a greater F_z can be produced in CMJ.

If the body configuration at each height of CG is the same, a greater F_z implies that muscle forces accelerating the body upwards are greater. Why would they be greater in CMJ than in SJ? A first possible explanation is that muscle stretch occurring during the countermovement in CMJ triggers neural responses (13,23) that, during the propulsive phase, help raise muscle stimulation, and hence force, over and above that in SJ. A second possible explanation is that muscle stretch in CMJ enhances the force-producing capacity of the contractile machinery (11,14,15,18,25). A third possible explanation assumes

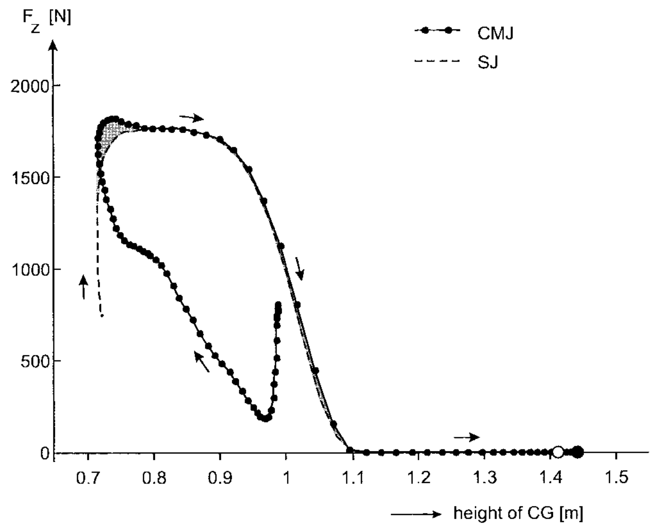

FIGURE 1—Vertical ground reaction force (F_z) plotted against height of center of gravity (CG) for a countermovement jump (CMJ) and a squat jump (SJ) of a single subject (data from (5)). ***Arrows*** **indicate the direction of time;** ***dots*** **on curve of CMJ have been plotted at 10-ms intervals. The** ***shaded area*** **represents the surplus of effective energy gained in CMJ, which ultimately causes jump height in CMJ (*****closed circle*****) to be greater than that in SJ (*****open circle*****).**

that both in CMJ and SJ the muscle fibers are on the descending limb of their force–length relationship at the start of propulsion, but that in CMJ, due to stretching of series elastic elements, they are less beyond optimum length and hence can produce greater force over the first part of their shortening range (15). Stretching of series elastic elements also implies storage of elastic energy, which can be reutilized during the propulsion phase. However, although having series elastic elements does contribute to maximum jump height by the positive effect on the rate at which energy can be released (4,24), it cannot explain differences in jump height among various types of jumps (1,6,27). A fourth possible explanation offered in the literature builds on the fact that muscle active state (essentially the fraction of actin binding sites available for cross-bridge formation) develops at a finite rate (3). In CMJ, active state can be developed during the preparatory countermovement, but in SJ, the active state inevitably develops during the propulsion phase, causing the force and muscle work produced over the first part of this phase (e.g., the first 5 cm in Fig. 1) to be submaximal. This possible explanation has been introduced by Asmussen and Sørensen in 1971 (3) and reiterated by many others (5,12,19,22,26,27). A final possible explanation is that the subject has superior coordination in CMJ; after all, if the subject is used to making CMJ but not to making SJ, he might have optimized his coordination for CMJ but not for SJ. This would then allow the subject in CMJ to realize at each height of CG a more favorable body configuration (with muscles operating in a more favorable region of their force-length relation), or a more favorable combination of joint angular velocities (with muscles operating in a more favorable region of their force–velocity relation), or more effective transfer from muscle forces to vertical acceleration of CG, and ultimately help the subject prevent premature take-off (7). Needless to say, the possible explanations are not mutually exclusive.

To systematically investigate why jump height is greater in CMJ than in SJ, experiments on human subjects are unsuitable, if for no other reason that crucial variables such as individual muscle forces and contractile element lengths cannot be measured. Therefore, researchers have turned to simulation models. Anderson and Pandy (1) performed simulations of CMJ and SJ with an optimal control model of the human musculoskeletal system to study the role of series elastic elements. Unfortunately, however, the results did not allow them to explain the difference in jump height between CMJ and SJ, for the simple reason that, contrary to expectation, the height of their simulated CMJ was 1 cm less than that of their simulated SJ.

Considering the abundance of studies on human subjects reporting greater jump height in CMJ than in SJ, and the plausible explanations offered for this finding, we felt that a greater jump height in CMJ than in SJ should also be borne out in a forward simulation study like the one conducted by Anderson and Pandy (1). In the present study, we shall show that this is indeed the case. The purpose of this study was to investigate whether the difference in jump height between CMJ and SJ could be explained by a difference in active state during the propulsion phase.

METHODS

For simulations of CMJ and SJ we used a two-dimensional forward dynamic model of the human musculoskeletal system (Fig. 2). The model, which had muscle stimulation as its only independent input, has been described in detail elsewhere (30). It consisted of four rigid segments representing feet, shanks, thighs, and a HAT segment representing head, arms, and trunk.

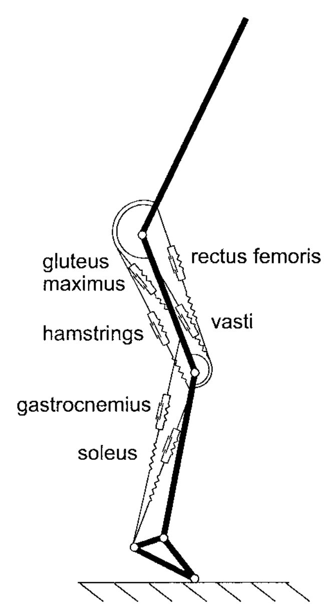

FIGURE 2—Schematic drawing of the model of the musculoskeletal system used for forward dynamic simulations. The model consists of four interconnected rigid segments and six muscle groups of the lower extremity, all represented by Hill-type muscle models.

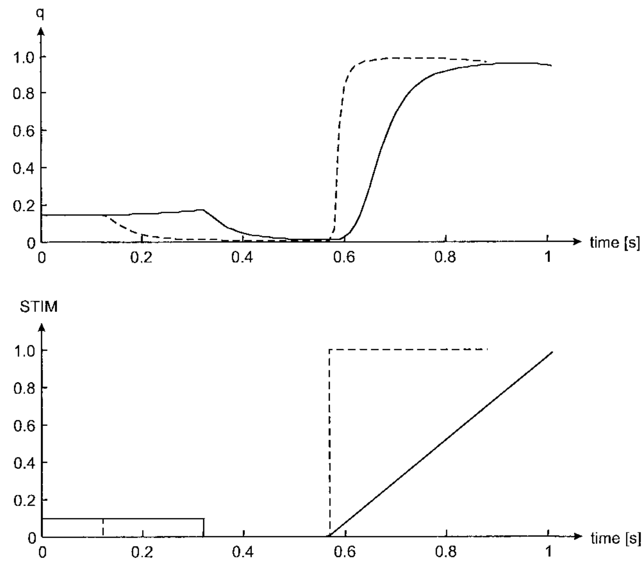

FIGURE 3—Stimulation (STIM) and active state (q) as a function of time for gluteus maximus during simulated maximum height CMJ, for the condition in which STIM increased instantaneously (*dashed line*) and the condition in which it increased at a rate of 2.2 s^{-1}. Note that q depends not only on STIM but also on length of contractile elements, which explains the slight initial increase of q in the latter condition during the first 300 ms. Note also that in this condition the propulsion phase lasted longer because force developed more slowly.

These segments were interconnected by hinge joints representing hip, knee, and ankle. In the skeletal submodel, the following six major muscle–tendon complexes (MTC) contributing to extension of the lower extremity were embedded: hamstrings, gluteus maximus, rectus femoris, vasti, gastrocnemius, and soleus. Each MTC was represented using a Hill-type muscle model. This muscle model, which has also been described in full detail elsewhere (28), consisted of a contractile element (CE), a series elastic element (SEE), and a parallel elastic element (PEE). Briefly, behavior of SEE and PEE was determined by a quadratic force-length relationship. Behavior of CE was more complex: CE contraction velocity depended on active state, CE-length, and force. Active state was not an independent input of the model but was manipulated indirectly via muscle stimulation STIM. Following Hatze (17), the relationship between active state and STIM, was modeled as a first order process. STIM, ranging between 0 and 1, was a one-dimensional representation of the effects of recruitment and firing frequency of α-motoneurons.

At the start of each simulation, the model was put in a starting position, and the initial STIM levels were set in such a way that static equilibrium was achieved. In the starting position of CMJ, small hip extension, knee flexion, and plantar flexion moments were needed (Fig. 4). To find a unique solution for the initial STIM-levels, we first demanded that hamstrings, rectus femoris, and vasti each produced a small force of 100 N (causing them to take up slack in SEE) and calculated the required STIM levels. Subsequently, we calculated the STIM levels for the other muscles that ensured equilibrium of the system as a whole (the corresponding forces automatically tensed SEE). In the starting position of SJ, hip extension, knee extension, and plantar flexion moments were needed for equilibrium, and we calculated the STIM levels that produced these moments under the constraint that each of the biarticular muscles produced a small force of 100 N. During propulsion, STIM of each muscle was allowed to switch several times. Each switch time initiated a change of STIM from its current level toward either its minimum of 0 or its maximum of 1. Any decrease of STIM toward 0 occurred instantaneously, any increase of STIM toward 1 occurred at a fixed rate (slope of the ramp in Fig. 3). Under these restrictions, the motion of the body segments, and therewith performance of the model, depended on a set of switch times. Thus, an optimization problem could be formulated: finding the combination of switch times that produced the maximum value of the height achieved by CG.

Comparison between CMJ and SJ, which was carried out for different conditions, always started with simulation of

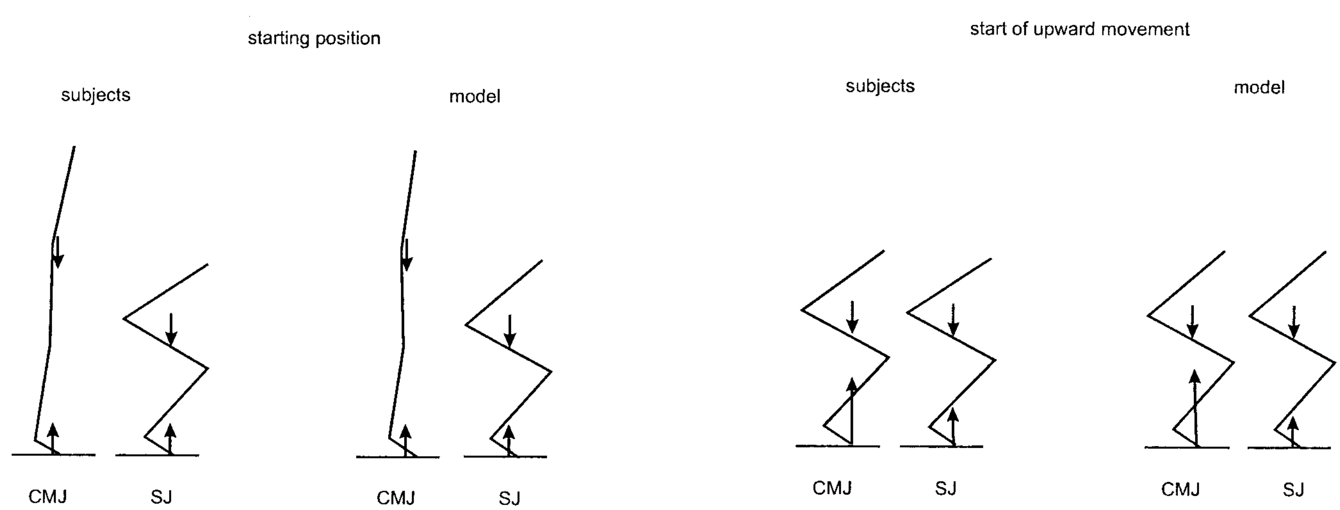

FIGURE 4—Body configurations at the start of CMJ and SJ as well as at the start of upward movement of the center of gravity (CG), for subjects (data from (5)) and for the simulation model. Note the difference between CMJ and SJ in ground reaction force magnitude (*arrows pointing upward*) at the start of upward movement of CG. *Arrows pointing downward* represent the force of gravity, plotted with the origin in CG.

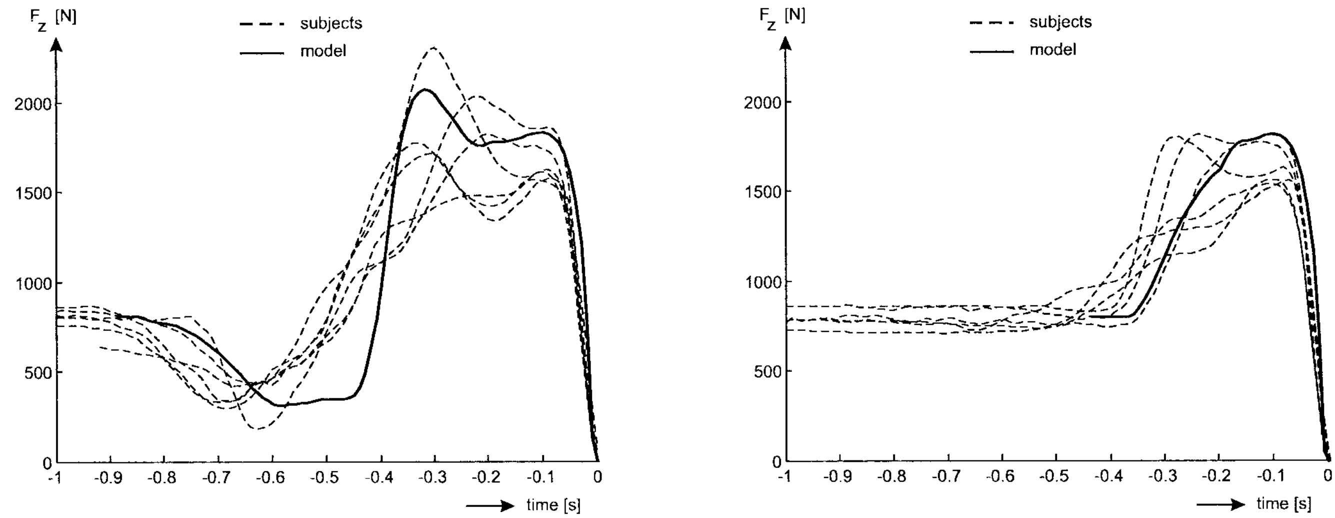

FIGURE 5—Time histories of the vertical ground reaction force in CMJ (left) and SJ (right) for individual subjects (data from (5)), and for the simulation model with the rate of increase of stimulation set to 2.2 s^{-1}. Time is expressed relative to the instant of take-off (t = 0).

CMJ from the average equilibrium starting position of human subjects (5) (see Fig. 4). To find the optimal solution for CMJ, two constraints were introduced by adding a penalty value to the optimization criterion. First, a penalty was set on deviation of the minimum height reached by CG from a prespecified value. By specifying a value derived from experimental data, we obtained simulated CMJ that could be compared with CMJ of subjects collected in a previous study (5). Second, a penalty was set on PEE forces in MTC other than soleus and gastrocnemius, which ensured that the configuration at the lowest CG height in CMJ could be reproduced in equilibrium. After solving the optimization problem under these constraints, the configuration at the lowest CG height reached in CMJ was selected and used as static starting configuration for simulation of SJ. For SJ, no constraints were used in the optimization.

CMJ and SJ were compared for different conditions, each of which involved a combination of a target minimum height of CG (71, 74, or 77 cm) and a prespecified rate of change of STIM during the ramp (ranging from 1.1 s^{-1} to infinite). For each condition, STIM for CMJ was optimized with the help of a parallel genetic algorithm (29). To obtain a near-maximal jump height, the algorithm arbitrarily ran for several hours using 15 1.8-MHz CPU from a students' computer lab (thereby performing 5,000–10,000 jumps). We made no painstaking attempt to find the globally optimal solution for CMJ, and indeed, when restarted, the genetic algorithm produced slightly different solutions that ranged in jump height by up to 2 mm. By contrast, for the corresponding SJ (i.e., the SJ starting from the configuration at the instant that CG reached its lowest height in one particular companion CMJ for the condition of interest), we exhaustively searched for the globally optimal solution using both the genetic algorithm and a simulated annealing algorithm (29). The difference in jump height in the solutions found by these two different algorithms was well below 1 mm for each of the conditions investigated, which gave us confidence that the reported SJ heights could not be improved further to any meaningful extent. In other words, if the optimization results would be in favor of any of the two jump types, they would be in favor of SJ.

Once the solutions were found for CMJ and SJ in each condition, we used them to determine the cause for differences in muscle work performed. Muscle work is the integral of muscle force with respect to MTC length, with muscle force depending on active state, CE length, and CE velocity. We estimated the effect of differences in active state between CMJ and SJ by substituting at each MTC length in SJ the active state at the same MTC length in CMJ, and subsequently recalculating muscle force and work. The same procedure was followed to estimate the effect of differences in CE velocity.

RESULTS

The simulation model behaved very well. First, in all conditions, regardless of the number of STIM switch times allowed per muscle, the optimization ended with a solution for CMJ in which each muscle only switched "off" and then "on," and in a solution for SJ in which each muscle only switched "on."

Second, optimal solutions for CMJ and SJ reasonably well reproduced the average configurations reported elsewhere for subjects (5), when the target minimum height of CG was set to the subjects' average value (Fig. 4). This was true regardless of the rate of increase of STIM. The only difference was that in the optimal solutions for CMJ the model tended to have the HAT segment rotated less forward at the minimum height of CG (with a compensatory further backward rotation of the leg segments) than the subjects. When the rate of increase of STIM was set to 2.2 s^{-1}, the average rate of increase of ground reaction force was satisfactorily reproduced with the model (Fig. 5), and over time, kinematics of simulated jumps satisfactorily resembled those of jumps by human subjects (Fig. 6).

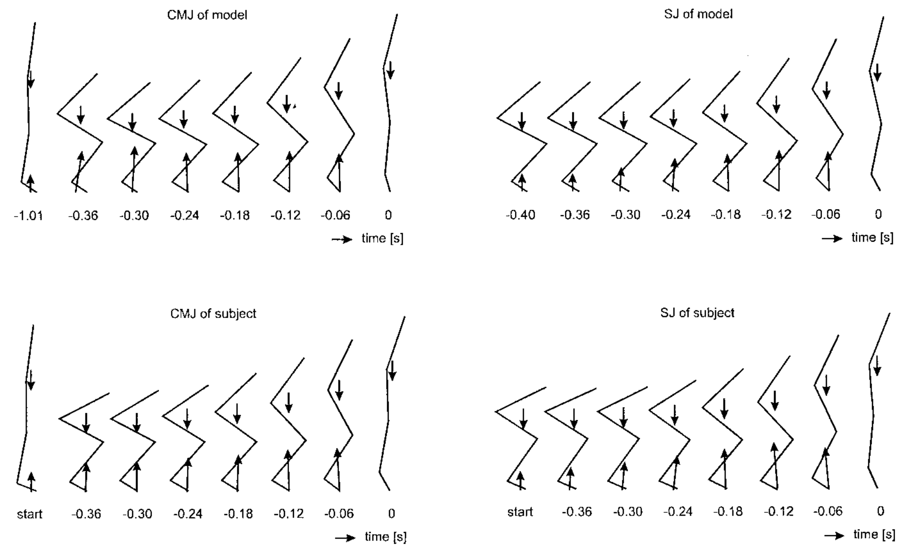

FIGURE 6—Stick diagrams at various time instants for CMJ (left) and SJ (right) for one subject (data from (5)) and for the simulation model with the rate of increase of stimulation set to 2.2 s^{-1}. *Arrows pointing upward* represent ground reaction forces; *arrows pointing downward* represent the force of gravity, plotted with the origin in the center of gravity. Time is expressed relative to the instant of take-off (t = 0).

Third, maximum jump heights of CMJ and SJ changed systematically with variations in conditions, and so did the difference in maximum height between CMJ and SJ. At a given target minimum height of CG, when the rate of increase of STIM was greater, maximum jump height was greater; the increase in height was smaller in CMJ than in SJ, so the difference in maximum height between CMJ and SJ became smaller (Fig. 7). At a given rate of increase of STIM, when the target minimum height of CG was lower, maximum jump height was greater (Fig. 7), which supports the contention that for a "fair" comparison of CMJ and SJ it must be ensured that the starting height of CG in SJ matches the lowest height of CG reached in CMJ (1,5).

Regardless of condition, maximum height in CMJ was greater than that in SJ. Even when stimulation was switched instantaneously to its new value, the difference in jump height was still on the order of 0.4 cm. The latter is not surprising, because active state follows STIM via a first-order process and hence does not become maximal instantaneously (Fig. 3).

We decided to further analyze the difference in jump height between CMJ and SJ for the condition in which the target minimum CG height was 0.74 m and STIM increased at a rate of 2.2 s^{-1}. In this condition, the maximum CG height reached was 1.530 m in CMJ and 1.510 m in SJ (Fig. 8), corresponding to an increase in effective energy during the propulsive phase of 637 J and 621 J, respectively. The total work output of the muscles during the propulsion phase was 729 J in CMJ and 710 J in SJ (Table 1), which means that the efficacy ratio (the fraction of muscle work converted into effective energy) was 0.86 in CMJ and 0.87 in SJ. The greater work in CMJ was due to a greater work output of hamstrings and gluteus maximus in CMJ (Table 1). Figure 9 presents for gluteus maximus the force, active state, and CE-shortening velocity as a function of MTC length. The work done during the propulsion phase is equal to the

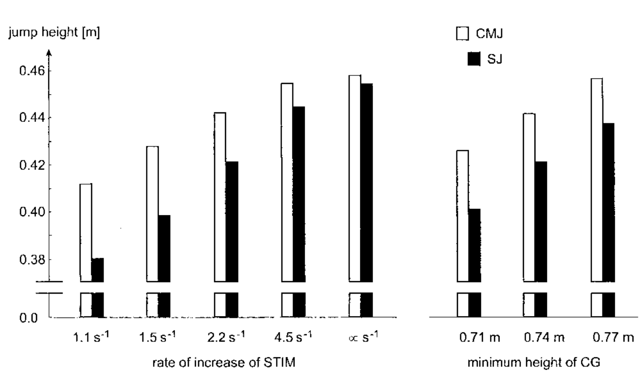

FIGURE 7—Maximum jump height of the simulation model for CMJ and SJ at different rates of increase of stimulation with the same target minimum height of the center of gravity (0.74 m, left), and at different target minimum heights of the center of gravity with the same rate of increase of stimulation (2.2 s^{-1}, right).

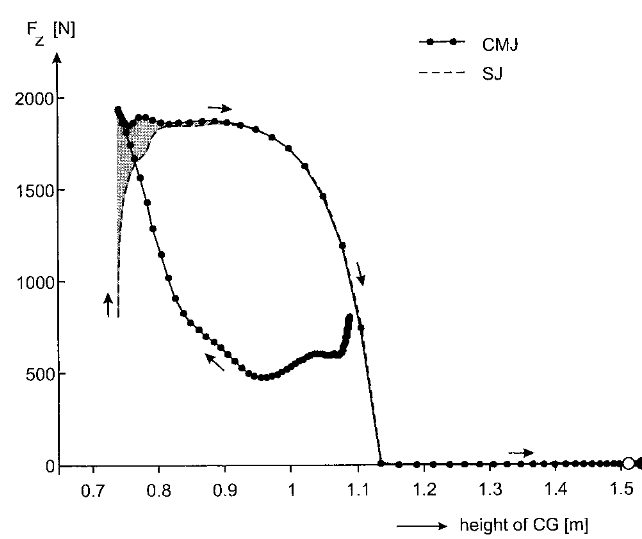

FIGURE 8—Vertical ground reaction force (F_z) plotted against height of center of gravity (CG) for the countermovement jump (CMJ) and the corresponding squat jump (SJ) of the model, in the condition in which the target minimum height of the center of gravity was set at 0.74 m and the rate of increase of stimulation was set at 2.2 s^{-1}. *Arrows* indicate the direction of time; *dots* on curve of CMJ have been plotted at 10-ms intervals. The *shaded area* represents the surplus of effective energy gained in CMJ, which ultimately causes jump height in CMJ (*closed circle*) to be greater than that in SJ (*open circle*).

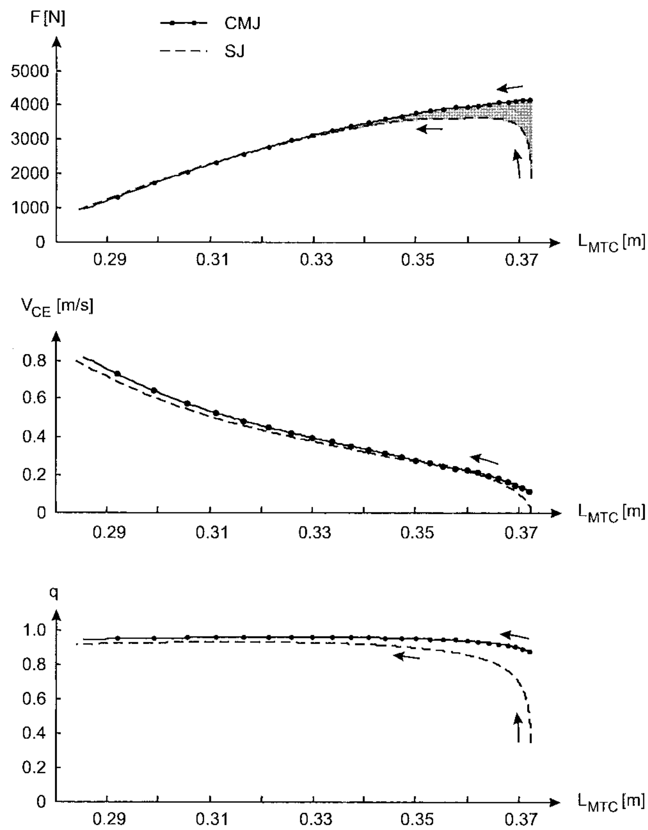

FIGURE 9—Force (F), shortening velocity of contractile elements (V_{CE}), and active state (q) of gluteus maximus as a function of MTC length (L_{MTC}) for the propulsion phase of the countermovement jump (CMJ) and the corresponding squat jump (SJ) of the model, in the condition in which the target minimum height of the center of gravity was set at 0.74 m and the rate of increase of stimulation was set at 2.2 s^{-1}. *Arrows* give the direction of time; *dots* on curve of CMJ have been plotted at 10-ms intervals. The *shaded area* represents the surplus of work output of gluteus maximus in CMJ as compared with SJ.

integral of force with respect to MTC length during this phase. The surplus of work for the propulsion phase in CMJ was attributed to a greater force over the first 30% of MTC shortening in the hip extensors. To estimate the effect of active state on the surplus work, we substituted at each MTC length in SJ the active state at the same MTC length in CMJ, and subsequently recalculated muscle force and work. In this thought experiment, the work output of the muscles in SJ increased by 33 J (Table 1), now causing a virtual work surplus in SJ of 14 J. However, in SJ the CE-shortening velocity remained lower than in CMJ (not surprisingly, because the take-off velocity was lower), and this could fully explain the virtual work surplus (Table 1).

DISCUSSION

In the literature, it has been described abundantly that people jump higher in CMJ than in SJ, and various possible explanations have been offered. To systematically investigate why jump height is greater in CMJ than in SJ, experiments on human subjects are unsuitable, and one needs to resort to simulation models. In the present study, a simulation model was used to investigate whether the difference in jump height between CMJ and SJ could be explained by a difference in active state during the propulsion phase.

TABLE 1. Work (J) produced by the model's muscle–tendon complexes (MTC) during the propulsion phase in CMJ and SJ, for the condition in which the target minimum height of the center of gravity was set at 0.74 m and the rate of increase of stimulation was set at 2.2 s^{-1}.

	CMJ	SJ	CMJ-SJ	SJ, Corr. q	SJ, Corr. V_{CE}
Hamstrings	138	121	16	18	−2
Gluteus maximus	252	242	11	17	−6
Rectus femoris	10	11	−1	−6	4
Vasti	204	208	−4	4	−8
Gastrocnemius	42	44	−2	−2	0
Soleus	84	85	−1	1	−2
Total	729	710	19	33	−14

All values are for left and right muscles together. Work is the integral of force with respect to MTC length. For SJ, we also substituted at each MTC length the active state occurring at the same MTC length during CMJ and calculated the change in work (SJ, corr. q). The same procedure was followed for the velocity of contractile elements (SJ, corr. V_{CE}). Corr., correction.

If effects are to be evaluated quantitatively, a realistic model is needed. In previous studies it has been shown that the model produces SJ that closely resemble jumps of human subjects (4), and in the present study, it has been shown that the same holds for CMJ (Figs. 4 and 6). Although different subjects converge toward a common kinematic pattern at the end of the propulsion phase, there is substantial interindividual variation in body configuration in the first part of the propulsion phase (7), and there is also considerable interindividual variation in the rate at which the ground reaction force increases (Fig. 5). In SJ, the simulated maximum height jumps fit well within the confidence intervals corresponding to the interindividual variation (Fig. 5), although admittedly in CMJ the ground reaction force increased faster in the model than in the subjects. Jump height of the model (45.6 cm in CMJ, 43.7 cm in SJ) was only slightly less than that of the human subjects from which the initial conditions were derived (48.1 ± 3.6 cm for CMJ and 44.7 ± 4.4 cm for SJ (5)). Overall, however, the model seemed realistic and suitable to investigate to what extent the difference in jump height between CMJ and SJ could be explained by a difference in active state during the propulsion phase.

In the simulations performed in this study, maximum jump height in CMJ was always greater than that in SJ, regardless of condition. This was in line with findings in studies on human subjects but contrary to the result of Anderson and Pandy (1), who found the height of their simulated CMJ to be 1 cm less than that of their simulated SJ. Anderson and Pandy did not search in their methodology for possible explanations of this peculiar finding but instead called into question the experimentally observed differences in jump height. In our view, however, it is more likely that the height realized in their simulated CMJ was not, in fact, the maximally achievable height. What Anderson and Pandy did was define a set of discrete times ("control nodes") at which muscle stimulation levels could change. Thus, it was impossible for a muscle to switch its stimulation in the interval between two "control nodes," which would perhaps have resulted in submaximal jump height in CMJ (and SJ, for that matter).

In our simulation model, which did jump higher in CMJ than in SJ, no reflexes or potentiation were incorporated and all simulated jumps corresponded to optimal solutions. This means that in the model the greater jump height in CMJ was completely due to the fact that in CMJ active state could develop during the preparatory countermovement, whereas in SJ it inevitably developed during the propulsion phase (Figs. 8 and 9). This allowed the hip extensor muscles to produce more force and more work during shortening in CMJ (Fig. 9), which was reflected in a higher F_z over the first 5 cm of upward motion of CG (Fig. 8) and in a greater jump height. In fact, in our thought experiment, in which we introduced in SJ the advantage of a higher active state during shortening as found in CMJ, we even ended up with a virtual muscle work surplus in SJ as compared with CMJ (Table 1). This virtual work surplus, however, could be explained by the fact that the CE-shortening velocities remained lower in SJ than in CMJ (Table 1).

The greater force and work that the hip extensor muscles could produce over the first part of shortening in CMJ could easily cause jump height to be about 2 cm greater in CMJ than in SJ (Fig. 7). Obviously, the difference in jump height between CMJ and SJ decreased when STIM increased faster (Fig. 7), because the latter caused a reduction of the distance covered at submaximal active state in SJ. Considering the variation among subjects in the rate at which they developed force (Fig. 5), it might be expected that the difference in jump height between CMJ and SJ also varies among subjects; a large difference is expected in subjects that build up force slowly, whereas a small difference is expected in subjects that build up force quickly. However, the resolution of experimental studies might be too low to detect such subtle differences. More importantly, according to the simulations, jump height may increase by several centimeters if active state is developed more quickly (Fig. 7). This raises the question why some subjects develop active state and force so slowly (Fig. 5). It has been speculated elsewhere (8,9) that subjects may lower the rate of muscle stimulation because this benefits stability. It would perhaps be interesting to study if subjects can learn to increase their stimulation faster, and if so, whether this indeed helps them to jump higher.

REFERENCES

1. Anderson, F. C., and M. G. Pandy. Storage and utilization of elastic strain energy during jumping. *J. Biomech.* 26:1413–1427, 1993.
2. Asmussen, E., and F. Bonde-Petersen. Storage of elastic energy in skeletal muscles in man. *Acta Physiol. Scand.* 91:385–392, 1974.
3. Asmussen, E., and N. Sørensen. The "wind up" movement in athletics. *Le Travail Humain* 34:147–156, 1971.
4. Bobbert, M. F. Dependence of human squat jump performance on the series elastic compliance of the triceps surae: a simulation study. *J. Exp. Biol.* 204:533–542, 2001.
5. Bobbert, M. F., K. G. Gerritsen, M. C. Litjens, and A. J. Van Soest. Why is countermovement jump height greater than squat jump height? *Med. Sci. Sports Exerc.* 28:1402–1412, 1996.
6. Bobbert, M. F., P. A. Huijing, and G. J. van Ingen Schenau. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med. Sci. Sports Exerc.* 19:332–338, 1987.
7. Bobbert, M. F., and A. J. van Soest. Why do people jump the way they do? *Exerc. Sport Sci. Rev.* 29:95–102, 2001.
8. Bobbert, M. F., and J. P. Van Zandwijk. Dynamics of force and muscle stimulation in human vertical jumping. *Med. Sci. Sports Exerc.* 31:303–310, 1999.
9. Bobbert, M. F., and J. P. van Zandwijk. Sensitivity of vertical jumping performance to changes in muscle stimulation onset times: a simulation study. *Biol. Cybern.* 81:101–108, 1999.
10. Bosco, C., I. Tarkka, and P. V. Komi. Effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercise. *Int. J. Sports Med.* 3:137–140, 1982.
11. Cavagna, G. A., B. Dusman, and R. Margaria. Positive work done by a previously stretched muscle. *J. Appl. Physiol.* 24:21–32, 1968.
12. Chapman, A. E., G. E. Caldwell, and W. S. Selbie. Mechanical output following muscle stretch in forearm supination against inertial loads. *J. Appl. Physiol.* 59:78–86, 1985.
13. Dietz, V., D. Schmidtbleicher, and J. Noth. Neuronal mechanisms of human locomotion. *J. Neurophysiol.* 42:1212–1222, 1979.
14. Edman, K. A., G. Elzinga, and M. I. Noble. Enhancement of mechanical performance by stretch during tetanic contractions of vertebrate skeletal muscle fibres. *J. Physiol.* 281:139–155, 1978.
15. Ettema, G. J., P. A. Huijing, and A. de Haan. The potentiating effect of prestretch on the contractile performance of rat gastrocnemius medialis muscle during subsequent shortening and isometric contractions. *J. Exp. Biol.* 165:121–136, 1992.
16. Harman, E. A., M. T. Rosenstein, P. N. Frykman, and R. M. Rosenstein. The effects of arms and countermovement on vertical jumping. *Med. Sci. Sports Exerc.* 22:825–833, 1990.
17. Hatze, H. *A Myocybernetic Control Model of Skeletal Muscle.* Pretoria: University of South Africa, 1981, pp. 31–42.
18. Herzog, W., R. Schachar, and T. R. Leonard. Characterization of the passive component of force enhancement following active stretching of skeletal muscle. *J. Exp. Biol.* 206:3635–3643, 2003.
19. Jaric, S., P. Gavrilovic, and V. Ivancevic. Effects of previous muscle contractions on cyclic movement dynamics. *Eur. J. Appl. Physiol. Occup. Physiol.* 54:216–221, 1985.
20. Komi, P. V., and C. Bosco. Utilization of stored elastic energy in leg extensor muscles by men and women. *Med. Sci. Sports* 10: 261–265, 1978.
21. Kubo, K., Y. Kawakami, and T. Fukunaga. Influence of elastic properties of tendon structures on jump performance in humans. *J. Appl. Physiol.* 87:2090–2096, 1999.
22. Levine, W. S., F. E. Zajac, M. R. Belzer, and M. R. Zomlefer. Ankle controls that produce a maximal vertical jump when other joints are locked. *IEEE Trans. Auto. Control* 28:1008–1016, 1983.
23. Melvill-Jones, G. M., and D. G. Watt. Observations on the control of stepping and hopping movements in man. *J. Physiol.* 219:709–727, 1971.
24. Pandy, M. G. An analytical framework for quantifying muscular action during human movement. In: *Multiple Muscle Systems: Biomechanics and Movement Organization*, J. M. Winters and S. L.-Y. Woo (Eds.). New York: Springer, 1990, pp. 653–662.
25. Rassier, D. E., W. Herzog, J. Wakeling, and D. A. Syme. Stretch-induced, steady-state force enhancement in single skeletal muscle fibers exceeds the isometric force at optimum fiber length. *J. Biomech.* 36:1309–1316, 2003.
26. Svantesson, U., G. Grimby, and R. Thomee. Potentiation of concentric plantar flexion torque following eccentric and isometric muscle actions. *Acta Physiol. Scand.* 152:287–293, 1994.
27. van Ingen Schenau, G. J. An alternative view to the concept of utilization of elastic energy in human movements. *Hum. Mov. Sci.* 3:301–336, 1984.
28. van Soest, A. J., and M. F. Bobbert. The contribution of muscle properties in the control of explosive movements. *Biol. Cybern.* 69:195–204, 1993.
29. van Soest, A. J., and L. J. Casius. The merits of a parallel genetic algorithm in solving hard optimization problems. *J. Biomech Eng.* 125:141–146, 2003.
30. van Soest, A. J., A. L. Schwab, M. F. Bobbert, and G. J. van Ingen Schenau. The influence of the biarticularity of the gastrocnemius muscle on vertical-jumping achievement. *J. Biomech.* 26:1–8, 1993.